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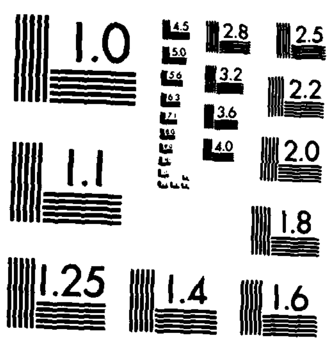

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Optical Waveguide Characterization Using Grating Couplers

D. G. HEFLINGER
Electronics Research Laboratory
The Aerospace Corporation
El Segundo, CA 90245

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15 December 1984

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Charles C Neidhart

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Joseph Hess

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Optical waveguides of GaAlAs were experimentally investigated using the grating coupler. A convenient measurement to reference input-coupling angles to the normal is described. This referencing capability enables the accurate characterization of a single mode waveguide. The measurement is applicable to the determination of the effective refractive index of quaternary waveguides, and thus could assist in the fabrication of GaInAsP/InP distributed feedback and distributed Bragg reflector lasers.

PREFACE

The author would like to thank E. M. Garmire, W. R. Fenner, and J. W. Niesen for their helpful discussions and J. A. Osmer for growing the GaAlAs waveguide. The author would also like to thank L. W. Casperson for advice on the thesis in which these ideas were first developed.

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I. INTRODUCTION

The need for semiconductor lasers with stable operation at high modulation rates has renewed interest in distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers.[1] Both DFB and DBR lasers incorporate a grating on an optical waveguide to produce wavelength selective feedback. In order to choose the grating period for distributed feedback, a knowledge of the propagation characteristics of the dielectric waveguide is required. This report considers an experimental technique for characterizing the propagation constants of an optical waveguide applicable to researchers involved in fabricating quaternary distributed feedback lasers.

Either a prism or a grating can be used to couple light into a dielectric waveguide. The prism relies on evanescent coupling and can be difficult to use with high refractive index waveguides made from III-V semiconductors. Thus grating coupling to III-V semiconductor waveguides is experimentally more feasible. Grating coupling at 1.15 μm in a GaAlAs waveguide was reported by Alferov et al.[2] in 1976, but has not been extensively referenced in the American literature. In this report, similar experiments are presented along with an additional measurement allowing a convenient determination of normal incidence which is crucial to the accurate determination of the effective refractive index.

II. THEORY

The modes of propagation of a dielectric waveguide are characterized by the propagation constant, β. The propagation constant is related to the effective refractive index by

$$\beta = k_o \, n_{eff}, \qquad (1)$$

where k_o is the free-space propagation constant. Light can be coupled into an allowed mode of propagation when it is incident at the appropriate angle to the grating incorporated on the surface of the waveguide. This coupling action is described by the relation

$$Z \equiv \frac{\Lambda}{\lambda_o} n_{eff} = p + \frac{\Lambda}{\lambda_o} n_1 \sin(\phi). \qquad (2)$$

Here, λ_o corresponds to the free-space wavelength of light, Λ is the period of the waveguide, ϕ is the coupling angle from the normal to the waveguide surface, p is the order of coupling, and n_1 is the index of the cladding layer through which the light is coupled. The equation has been written in terms of the normalized effective refractive index, defined here as Z.

The coupling behavior of Eq. (2) is plotted in Fig. 1. For this plot, the grating period and wavelength of light have been held constant at 0.3507 μm and 1.1523 μm, respectively. This allows a normalized value of n_{eff} to be plotted against the coupling angle ϕ. The plot corresponds to an asymmetric waveguide with GaAlAs providing the "substrate" and air providing the cover for a guiding film layer of GaAs. The solid line corresponds to the angles coupled from the air, index 1.0, and the dashed line corresponds to the angles coupled from the substrate layer of index 3.28.

The calculation of the period of a DFB or DBR semiconductor laser depends on the effective refractive index of the waveguide as

$$\Lambda_{DFB} = \frac{q\lambda_o}{2n_{eff}} . \qquad (3)$$

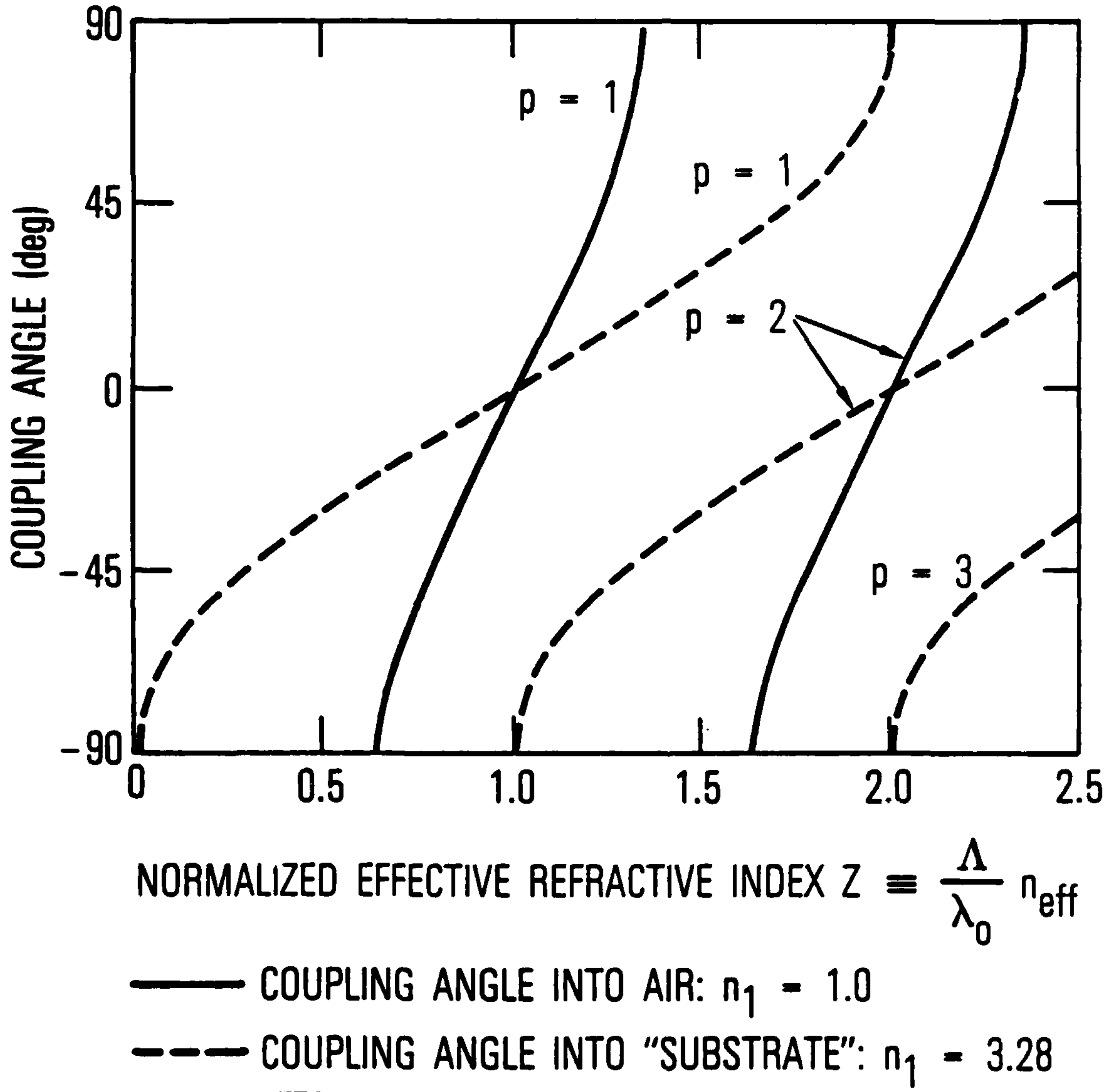

Figure 1. Coupling Angle as a Function of Normalized Refractive Index, $\Lambda = 3.35$, $\lambda_o = 1.2$ μm, TE_o Mode

ere, q is the diffraction order of the Bragg interaction. Thus, with a nowledge of the effective refractive index of the waveguide layer, the grat-ng for distributed feedback can be fabricated. Equation (2) indicates that he effective refractive index can be obtained from the measurement of the oupling angle, the wavelength of light, the bulk index of the cladding layer hrough which this light is coupled, and the grating period of the coupler.

The relative angles at which light couples into the waveguide can be easured with a calibrated rotation stage. However, experimentally referenc-ng these relative angles to the direction normal to the sample is generally ore difficult. A convenient experimental technique is described in this aper for making this reference measurement.

III. EXPERIMENT

To demonstrate this technique for characterizing an optical waveguide, a lding layer of GaAs and a "substrate" layer of GaAlAs with an aluminum ıcentration of 30% were grown by liquid phase epitaxy (LPE) on a supporting fer of GaAs. The grating was fabricated by holographic photolithography.[3] this process a layer of photoresist is spun over the surface of the veguide and exposed in a holographic interferometer. The developed otoresist relief pattern is then replicated into the surface of the GaAs veguide layer by ion beam etching. Any of the techniques in use for bricating submicron gratings can be used to make this diagnostic grating, ovided a rough estimate of the period needed for coupling at nearly normal cidence is possible. The period was measured using the diffraction at the ttrow angle.[3]

The coupling experiment used an infrared helium neon laser* with output 1.1523 μm in order to be away from the band gap absorption of the guiding yer of GaAs at 0.89 μm. The particular laser which was used supported a int additional tabulated[4] line at 1.1614 μm with an intensity 14% of the imary line. This additional laser line was identified to interpret the asured data. A calcite rotator was used to establish transverse magnetic M) input polarization, and an interference filter was used to block out the uorescence of the laser.

A waveguide sample, 4 mm square, was mounted on a rotation stage in order have t[illegible]ating surface nearly normal to the incident laser beam as picted in [illegible] The axis of rotation was made to coincide with the sition on the waveguide of the incident laser beam. When the sample was tated to an angle at which the grating could couple the laser light into an lowed mode, the guided light was detected from the output edge of the waveide. Detection was done by locating a photodetector at the image of a lens

pectra-Physics Stabilite (TM) model 120 infrared helium neon laser with odel 249 Spectra-Physics laser exciter.

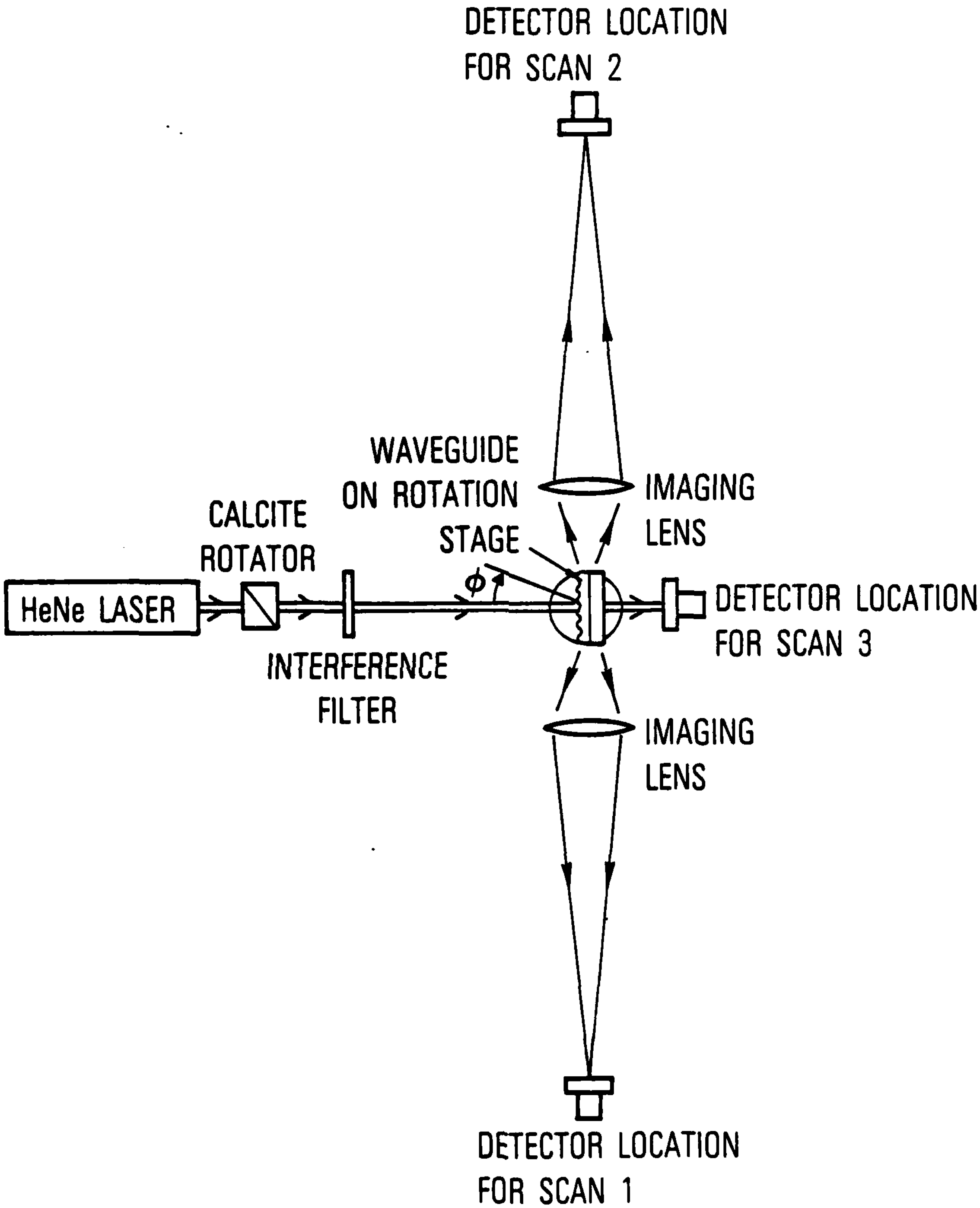

Figure 2. Experimental Arrangement for Characterizing an Optical Waveguide Using a Grating Coupler

focused on the edge of the waveguide as indicated in Fig. 2. A potentiometer was mechanically linked to the micrometer which adjusted the rotation stage in order to record the angle along the x-axis of a plotter. The light intensity from the detector was sent to the y-axis.

An experimental scan of the light intensity from each edge of the waveguide sample is depicted in the first two scans of Fig. 3. The waveguide supported three TM modes. When the weak secondary lasing line is included, there is a total of six coupling angles for each direction identified in Fig. 3. The crucial measurement for obtaining the effective refractive index is the coupling angles. A relative measurement between two modes depends only on the accuracy of the angles marked on the rotation stage. However, an absolute measurement with respect to the normal of the waveguide surface is necessary to find the effective refractive index if only one mode is supported by the guide.

An additional measurement which can provide this absolute angle reference is performed by locating the photodetector behind the waveguide sample and recording the intensity of the light transmitted through the sample.[5] The photodetector location for this transmission measurement is depicted in Fig. 2. Decreases in this intensity as a function of coupling angle indicate that the grating is capturing light and conveying it into the waveguide. This measurement, in conjunction with a measurement of the reflected intensity, was used by Dakss et al.[6] to determine the input-coupling efficiency of the grating coupler.

In the experiment reported here, the measurement provides an indication of the position of the angle normal to the surface of the waveguide. The bottom scan of Fig. 3 is the transmitted intensity as a function of angle. Each dip in the curve corresponds to a coupling angle for a particular mode of the waveguide. The symmetry of these dips in the curve about the dashed line arises from coupling into both directions of the waveguide, as can be seen from the correlation to the light intensity scans recorded above from each edge. This line of symmetry indicates the angle normal to the waveguide surface and thus provides an absolute reference from which to measure the coupling angles.

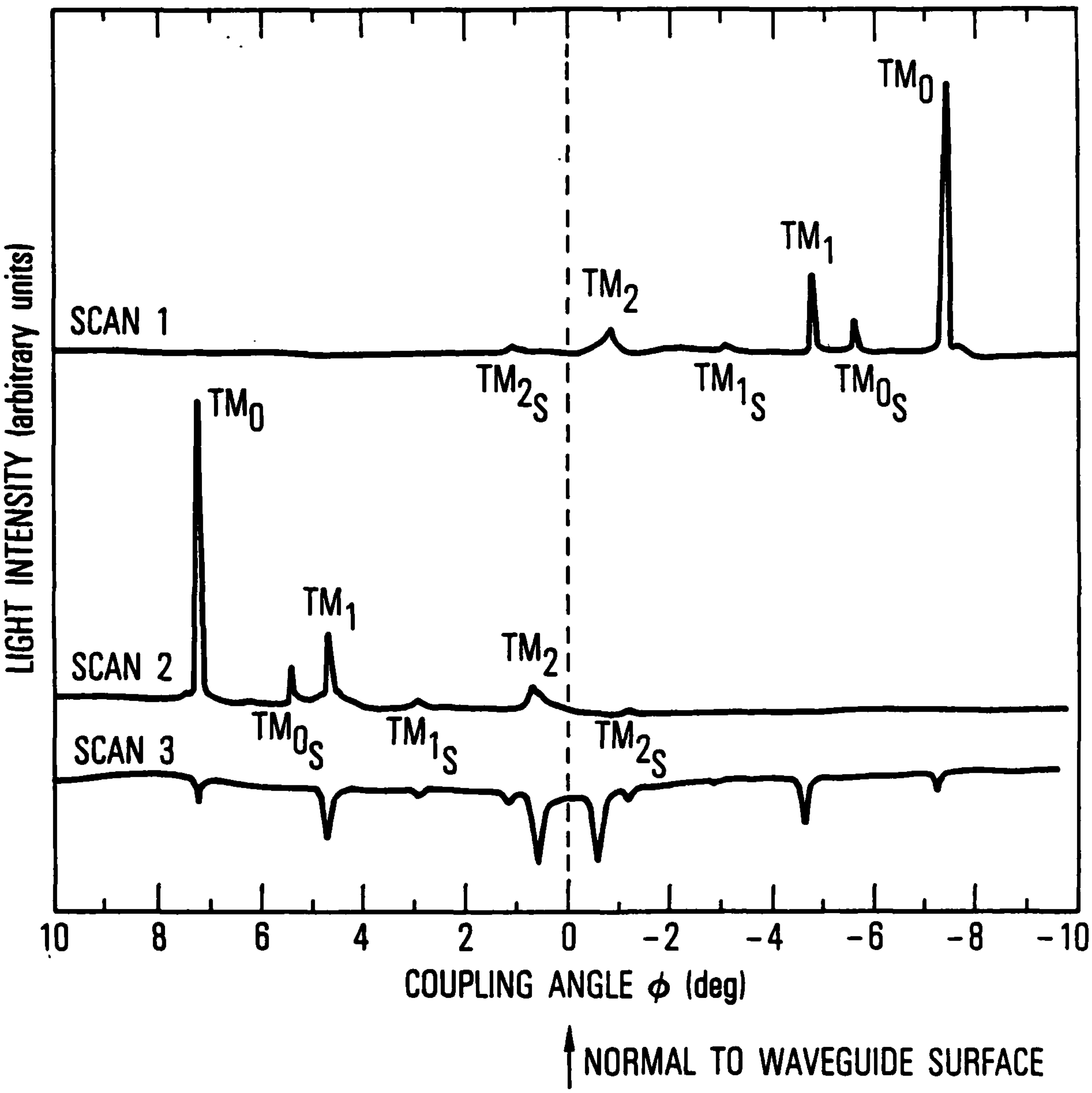

Figure 3. Recorded Scans of Light Intensity from Locations Depicted in Figure 2 as a Function of Coupling Angle ϕ

From the recorded scans in Fig. 3, the absolute coupling angles from air were determined and are tabulated in Table I. With knowledge of the free-space wavelength at 1.1523 μm, the grating period, measured to be 0.3507± 0.0001 μm, and the diffraction order $p = 1$, the effective refractive index for each mode was determined using Eq. (2). For a comparison, the effective refractive indices were also obtained by measuring the parameters needed for theoretical modeling.[7] The guiding film layer thickness was measured to be 1.6±0.1 μm using an optical microscope. The bulk refractive indices of each layer were obtained by measuring the photoluminescence wavelength peak indicating the aluminum concentration of each layer. The concentration was then correlated to the bulk refractive index via data given by Casey and Panish.[7] This correlation gave a guiding film layer index of 3.431 and a substrate layer index of 3.282. The cover layer index was taken as 1.0 for air. Using these values, the effective refractive index for each mode was calculated and appears in Table I.

Table I. Comparisons of Effective Refractive Indices for a GaAlAs Optical Waveguide at 1.1523 μm

Mode of Propagation	TM_0	TM_1	TM_2
Coupling angle ϕ (degrees)	7.3±.1	4.9±.1	0.7±.1
n_{eff} (via coupling angle)	3.41	3.37	3.30
n_{eff} (via theoretical model)	3.415	3.369	3.298

IV. APPLICATION

Although the waveguide sample evaluated here supported more than one mode, the technique for determining the absolute coupling angles via the symmetry of the transmission curve allows a single mode waveguide to be characterized. Without this measurement of the absolute angle, several relative angles between modes would be necessary to obtain an analytical fit. This capability of characterizing a single mode waveguide is important since most distributed feedback lasers use waveguides which support only one mode.

There are some limitations to the transmission measurement. The transmission measurement requires that the laser light be able to pass through the supporting wafer of GaAs without absorption. By using an infrared helium neon laser, the band gap absorption of the GaAs wafer did not interfere with the measurement. However, the characterization of a GaAlAs DFB or DBR laser structure at its lasing wavelength would require using wavelengths which would be absorbed by the supporting GaAs.

Two alternative techniques could be used to surmount this problem. Specular reflection off the surface of the waveguide could be used to provide a reference to normal. Alternatively, two photodetectors could be simultaneously used to detect the coupled light that emerges from each edge. The two signals could be combined electronically to generate a symmetric scan. The normal reference angle would be identifiable just as in the transmission measurement.

This simultaneous measurement should work provided that the guided light does not get substantially output-coupled by the remaining grating between the input beam and the edge of the waveguide. For the waveguide studied in this paper, output-coupling interfered with the measurement and required the incident beam to be positioned near the edge from which light was to be detected. Thus each edge had to be measured separately.

This band gap absorption will not be a problem for quaternary DFB and DBR lasers. Using a collimated quaternary laser with lasing output around 1.5 μm, the InP supporting wafer will not severely interfere with the transmission measurement. The band gap of InP at 0.9 μm is conveniently smaller than the wavelengths of current interest for quaternary DFB and DBR lasers. Although the experimental technique has been demonstrated here using a GaAlAs optical waveguide, the technique appears applicable to GaInAsP/InP optical waveguides incorporated in quaternary DFB and DBR lasers.

V. CONCLUSIONS

The experiment presented in this report has described the procedure for characterizing III-V optical waveguides using a grating coupler. A GaAlAs optical waveguide was employed for this experiment. The discovery of a transmission measurement has been reported which enables the coupling angles to be referenced to normal. This additional measurement allows a single mode waveguide to be accurately characterized. With this procedure, the effective refractive index can be experimentally obtained and utilized for the calculation of the period of a distributed grating reflector.

The additional capability provided by the transmission measurement appears to be applicable to the fabrication of quaternary DFB and DBR lasers since the band gap absorption of InP will not interfere with the transmission measurements made at the lasing wavelength of these lasers.

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